520. The combined sensor using bridge circuit supplied by current sources for simultaneous measurement of two parameters

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Abstract. This paper describes a new features of resistance bridge supplied by two current sources placed in opposite arms. The possibility to simultaneous measurements of temperature and strain has been achieved by using this technique and it is described with some theoretical considerations. Theory is mentioned along with data to confirm that the temperature and strain gauge resistance changes are sensed without appreciable error. Also the results of an experiment confirm this approach. To complete these considerations the uncertainty of both temperature and strain changes is calculated. Also the possibility to apply this technique in biomechanics is discussed.

Keywords: multiparameter measurements, strain and temperature measurement, bridge circuit, uncertainty calculation.

Introduction

The traditional method for strain and temperature measurement during hot structural testing requires two independent sensors at the desired location. This approach is well known since the end of 19^{th} century and developed during next decades. In 1993 Allen R. Parker proposed the simultaneous measurement of temperature and strain using four connecting wires [1]. This technique implements Anderson's theory [2] and needs a special analog demultiplexer design. Two sensors are combined to form one sensor called the thermostrain gauge. The process mixes the signals of both sensors. One part of literature describing Anderson current loop circuit and its implementations is available through *http://www.vm-usa.com/links.html.*

In most applications the sensor's thermal error (drift of sensor's offset and span) is compensated in the digital part of a conditioner by proper correction algorithms. In pressure measurement applications a piezoresistive sensor can be powered by adjustable current source combined with programmable-gain amplifier and external trimmable resistors (i.e. in signal conditioner MAX1450) [3], or two amplifiers and two digitally controlled potentiometers [4], or four digital-to-analog converters resulting in a temperature-depended bridge voltage (i.e. in MAX1452) [5].

In a mass production of silicon piezoresistive-bridge pressure sensors, the sensor's error correction is often affected by use of a laser or abrasive trimming machine which trims resistors and thermistors in the signal conditioning circuit to the values required for offset and sensitivity compensation (i.e. in X-ducer piezoresistive pressure bridge-sensors [6], or NPC series of GE Novasensor pressure sensors [7]).

Since 2001 the new type of circuit for such measurements and for the primary signal conditioning on the input analogue part of instrumentation channels has been proposed [8]. It consists of the bridge circuit supplied by two equal current sources placed in opposite arms. This circuit was named as **double current bridge** (**2J**). Author has developed his idea the next years and the results are described in [9-11].

This paper shows that two identical current sources supplying classical resistance bridge cause this measuring circuit useful for simultaneous measurement of temperature and strain. Furthemore, the quantities are sensed without appreciable uncertainties.

2J Bridge with Two Active Arms

2J bridge proposed by Warsza differs from the Wheatstone bridge in the way of supplying. It is quite easy to arrange it for two variable measurements (Fig. 1). The bridge has two outputs: A-B and D-C. Two equal current supply sources *J* are connected in parallel to opposite arms (R_1, R_3) of the bridge – circuit a). But it is difficult in practical realization. If the excitations are not equal, the equations (1) and (2) have additional components which are dependent on the difference ΔJ [9, 10].

The bridge can also be supplied by single current source *J* switched over to the same arms – circuit b). Then each of the output voltages is held, summed up (1) in two cycles (the superposition theorem) and measured.

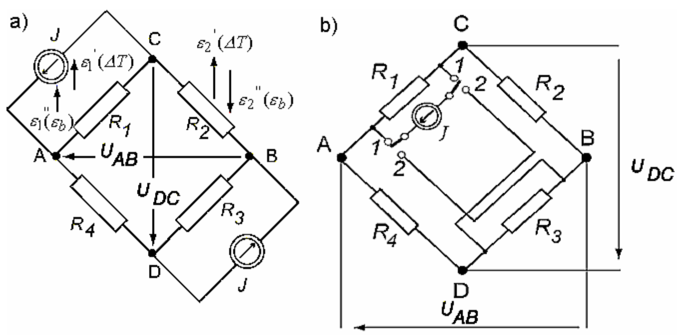

Fig. 1. Double current bridge circuits supplied by two current sources (a) or one switched (b)

$$U_{DC} = U_{DC_1} + U_{DC_2} \text{ and } U_{AB} = U_{AB_1} + U_{AB_2} \tag{1}$$

Such a supply causes compensation of thermoelectric voltages (of equal values) and independence of the current *J* direction.

The output voltages of these bridges are:

$$U_{DC} = J\,\frac{R_1R_2 - R_3R_4}{\sum R_i}\,,\ U_{AB} = J\,\frac{R_1R_4 - R_2R_3}{\sum R_i}\,, \tag{2}$$

where: $R_i=R_{i0}(1+\varepsilon_i)$, $\Sigma R_i=R_1+R_2+R_3+R_4$; R_{i0} - the initial nominal resistance, ε_i - the relative change of resistance.

Forms of U_{DC} and U_{AB} are similar to the voltage in unbalanced Wheatstone bridge supplied by current source. The outputs of the a) and b) circuits are balanced for the equal products of resistances in neighbouring bridge arms. After separation of resistance changes, the formulas mentioned above are

$$U_{DC} = J\frac{R_{10}R_{20}}{\sum R_{i0}} \frac{(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 + \varepsilon_1\varepsilon_2 - \varepsilon_3\varepsilon_4)}{1 + \frac{\sum R_{i0}\varepsilon_i}{\sum R_{i0}}} \tag{3a}$$

if $R_{10}R_{20} = R_{30}R_{40}$ and

$$U_{AB} = J\frac{R_{10}R_{20}}{\sum R_{i0}} \frac{(\varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4 + \varepsilon_1\varepsilon_4 - \varepsilon_2\varepsilon_3)}{1 + \frac{\sum R_{i0}\varepsilon_i}{\sum R_{i0}}} \tag{3b}$$

if $R_{10}R_{40} = R_{20}R_{30}$.

The all above conditions for nominal initial values of resistances are fulfilled if $R_{10} = R_{20} = R_{30} = R_{40} = R_0$.
Let us assume that sensors are in two arms of the bridge and their resistances vary and that the sum of all relative resistance increments is equal zero, i.e. $\sum_{i=1}^{4}\varepsilon_i = 0$. In equations (3a) and (3b) one can notice that one pair of relative resistance changes of the same index has the same sign and the other - opposite one. Additionally, these changes are small when using pairs of strain gauges, then $\varepsilon_i\varepsilon_j << \varepsilon_i + \varepsilon_j$. Assuming that: $R_3 = R_{30}$, $R_4 = R_{40}$ (which is tantamount to $\varepsilon_3 = \varepsilon_4 = 0$) the output voltages can be written as follow

$$U_{DC} = T_0 \frac{\varepsilon_1 + \varepsilon_2 + \varepsilon_1\varepsilon_2}{1 + \frac{\varepsilon_1 + \varepsilon_2}{4}} \quad \text{and} \quad U_{AB} = T_0 \frac{\varepsilon_1 - \varepsilon_2}{1 + \frac{\varepsilon_1 + \varepsilon_2}{4}} \tag{4}$$

If modules of the values $|\varepsilon_1|$, $|\varepsilon_2|$ are small enough, i.e. $|\varepsilon_1 \cdot \varepsilon_2| << |\varepsilon_1 + \varepsilon_2|$ and $|\varepsilon_1 + \varepsilon_2| << 4$ (for absolute changes it is $|\Delta R_1+\Delta R_2| << 2(R_{10} + R_{20})$, formulas (4) are simplified to

$$U_{DC} = T_0(\varepsilon_1 + \varepsilon_2) \quad \text{and} \quad U_{AB} = T_0(\varepsilon_1 - \varepsilon_2) \tag{5}$$

where: $T_0 = \frac{JR_0}{4}$ - the initial voltage sensitivity which is equal for both outputs.

The first output voltage is proportional to the sum and the other one to the difference of increments.

Example of Strain and Temperature Measurements

Taking the four terminal structure of the 2J bridge circuit into consideration, it can be applied for measuring techniques with the use of strain gauges. Two ways of placing the strain gauges on the beam are shown in Fig. 2. The first example can be used for one-axis strain and temperature measurement by using two strain gauges A and B. The second example can be used for 2-axis strain measurement when concentrated forces (moments) are applied in two directions (it will be the purpose of future investigations).

The resistance increments of strain gauges consist of two parts

($\varepsilon_1 = \varepsilon' + \varepsilon''$, $\varepsilon_2 = \varepsilon' - \varepsilon''$, respectively). One part is temperature increment , the other one is the increment (or decrement) due to mechanical stress (6). If there are two strain gauges of the same type, the relative temperature increments are of the same value and of the same sign.

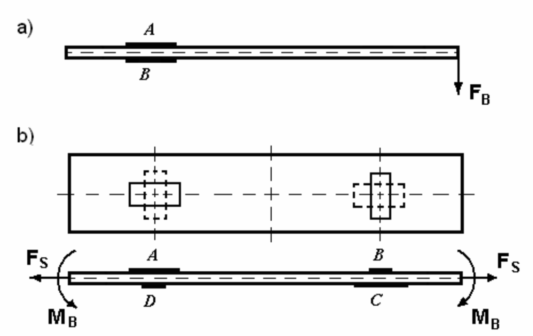

Fig. 2. One-axis (a) and two-axis (b) strain measurement, *A*,*B*,*C*,*D* – strain gauges, F_B - bending force, F_S - stretching force, M_B - bending moment

Additionally, if strain gauges are glued to a beam such that the first gauge is stretched and the other compressed (Fig. 2a) then the increments due to mechanical stress are of the opposite signs. They can be considered as linear for both measured quantities

$$\varepsilon_1^{'}(\Delta T) = \varepsilon_2^{'}(\Delta T) = \varepsilon^{'} = \alpha_T \cdot \Delta T \qquad \varepsilon_1^{''}(\varepsilon_b) = -\varepsilon_2^{''}(\varepsilon_b) = \varepsilon^{''} = k \cdot \varepsilon_b \tag{6}$$

From (5)

$$U_{DC} = T_0(\varepsilon^{'} + \varepsilon^{'}), \qquad U_{AB} = T_0(\varepsilon^{''} + \varepsilon^{''}) \tag{7}$$

where: α_T – the temperature coefficient of resistance, ΔT – change of temperature, $k = k_0(1 + \alpha_K \Delta T)$ – nominal gauge factor, ε_b – bending strain, α_K – temperature coefficient of gauge factor.
After substitution, both functions are as follows:

$$\varepsilon' = \alpha_T \cdot \Delta T = \frac{U_{DC}}{2T_0} = \frac{2}{JR_0} U_{DC} \quad \Rightarrow \Delta T = \frac{2U_{DC}}{JR_0 \alpha_T} \tag{8}$$

$$\varepsilon'' = k \cdot \varepsilon_b = \frac{U_{AB}}{2T_0} = \frac{2}{JR_0} U_{AB} \quad \Rightarrow \varepsilon_b = \frac{2U_{AB}}{JR_0 k} \tag{9}$$

Both measured quantities depend linearly on output voltages U_{AB} and U_{CD} (respectively), supplying current J and the parameters of the gauges.

Results of the experiment

The theoretical considerations have been verified in the experimental circuit of a transducer given in Fig 3. The switched current source was constructed with the use of LM317 and four MOSFET switches (STP20NE06L) which are characterized by low on-resistance R_{ON} = 0.06 Ω. The current excitation could be manually adjustable from 9 mA until 38 mA. The transistors worked in pairs – two switched on and two switched off at the same time. Their state of work was controlled by Atmega16 microcontroller port.

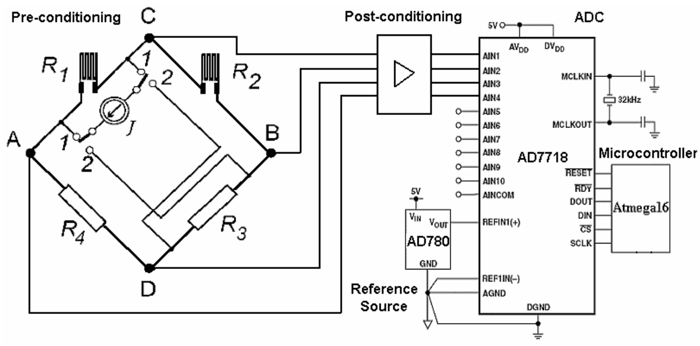

Fig. 3. Block diagram of the transducer system of double current bridge for simultaneous measurements of strain and temperature

The output voltages U_{AB} and U_{DC} (two of them of positive sign and another two of negative sign) were connected to 24-bit sigma-delta A/D converter (AD7718) via post-conditioning module. It consists of the instrumentation amplifiers (AD620AN) and ultra-precision voltage-dividers (MAX5491). The use of this module was necessary because AD7718 requires positive sign voltages of (0 - 2.56 V).

The data of the acquired voltages from the circuit outputs were processed by the microcontroller. The measurements were performed for two temperatures of a cantilever beam (23 °C and 65 °C) while the beam was being bent by a micrometer screw (Fig. 4).

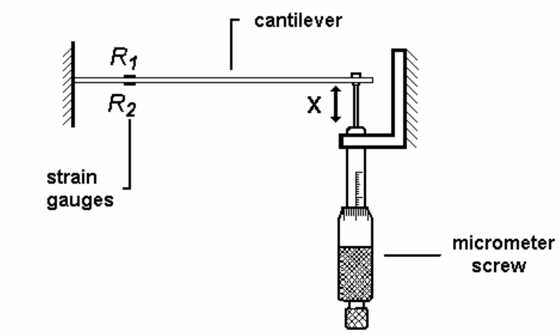

Fig. 4. Schematic view of the laboratory stand (the cantilever rectangle cross-section, width 20 mm, height 0.8mm, length 200mm, the distance from place of fixing 20mm)

The results of the experiment are shown in Fig. 5. It presents the diagrams of relative resistance increments ε in the function of the beam X deflection: $\varepsilon'(23)$, $\varepsilon'(65)$ – the temperature increment calculated for 23°C and for 65°C respectively, $\varepsilon_1(65, \varepsilon_b)$ – the increment due to mechanical stress in temperature 65°C, $\varepsilon''(\varepsilon_b)$ – the increment of mechanical stress after temperature compensation.

The regression method has been used to receive the values of straight lines the best fitted to data points. They are presented in Fig. 5 and defined by following equations:

$$\varepsilon'(65) = 0.0022X + 0.0710 \qquad \varepsilon_1(65, \varepsilon_b) = 0.0228X + 0.0196 \tag{10}$$

$$\varepsilon'(23) = 0.0021X \qquad \varepsilon''(\varepsilon_b) = 0.0226X = a\,X \tag{11}$$

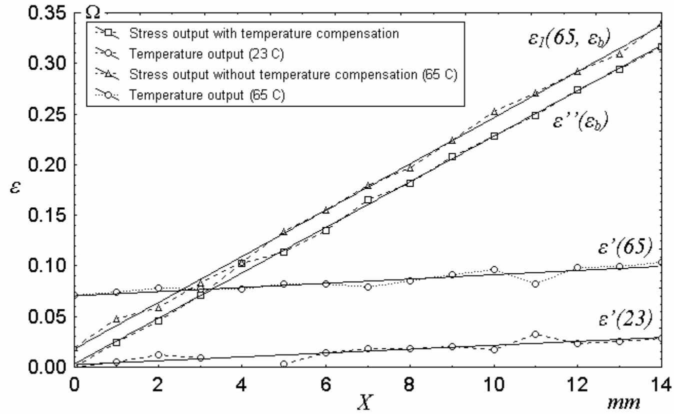

Fig. 5. Relative resistance increments ε in the term of the beam deflection X

Accuracy of the measurements

The nonlinearity error with respect to mechanical stress is 1.8% FSR (max) and 0.6% FSR in average. For the measurement of temperature changes the nonlinearity error is a little bigger - 2.5% FSR (max) and 1.0% FSR (average). Also the repeatability of measurements the mechanical stress and the changes of temperature for selected supplying current were tested in practice and calculated. The half value of sample standard deviations of the series of measurements was a parameter to estimate this feature (Table 1).

Table 1. Repeatability of measurements

J=14.6 mA, X=10 mm				
Nr	***ΔT*** *deg*	$\boldsymbol{\varepsilon_b}$	$\overline{\Delta T} = \frac{\sum \Delta T_i}{10}$	$\overline{\varepsilon_b} = \frac{\sum \varepsilon_{bi}}{10}$
1	19.56	0.219	19.58	0.219
2	19.54	0.218	$\frac{0.5 \cdot \delta_{n\Delta T}}{\overline{\Delta T}} \cdot 100\% \approx 0.1\%$	
3	19.54	0.218		
4	19.52	0.219		
5	19.58	0.219		
6	19.67	0.219	$\frac{0.5 \cdot \delta_{n\varepsilon}}{\overline{\varepsilon_b}} \cdot 100\% \approx 0.2\%$	
7	19.61	0.219		
8	19.52	0.218		
9	19.58	0.218		
10	19.66	0.218		
$0.5 \cdot \delta_n =$	0.026	0.0004		

On the base of equations (8), (9) and applying the well-known low of uncertainty propagation the relative standard uncertainties have been received

$$\frac{u^2(\Delta T)}{(\Delta T)^2} = \delta_{\Delta T}^2 = \delta_{U_{DC}}^2 + \delta_J^2 + \delta_{R_{10}}^2 + \delta_{\alpha_T}^2 \tag{12}$$

$$\begin{aligned}\frac{u^2(\varepsilon_b)}{(\varepsilon_b)^2} = \delta_{\varepsilon_b}^2 &= \delta_{U_{AB}}^2 + \frac{4}{d^2}\alpha_K^2 U_{DC}^2(\delta_{U_{DC}}^2 + \delta_{\alpha_T}^2 + \delta_{\alpha_K}^2) + \\ &+ \frac{1}{d^2}\alpha_T^2 R_{10}^2 J^2 k_0^2(\delta_J^2 + \delta_{R_{10}}^2 + \delta_{k_0}^2)\end{aligned} \tag{13}$$

where $d = 2U_{DC}\alpha_K + JR_{10}k_0\alpha_T$

The maximum errors of strain and temperature measurement obtained from the total differential method are presented by equations (12) and (13). They contain the following parameters:

- nominal resistance error δ_{R10} (the limiting error related to nominal resistance),
- nominal gauge factor error δ_{k0} (the limiting error related to nominal gauge factor),
- temperature coefficient of gauge factor error $\delta_{\alpha K}$ (the limiting error related to nominal coefficient),
- supplying current error δ_J (the limiting error related to nominal value of supplying current),
- voltage δ_{UAB} and δ_{UDC} errors (the limiting error related to current values of voltages),

From (12) one can notice that the maximum temperature measurement error depends only on the accuracy of voltage U_{DC}, supplying current J and nominal resistances R_0. The most significant component in the strain measurement error depends on the accuracy of U_{AB} voltage.

Conclusions

The 2J bridge which measures the real change of temperature of strain gauges in their localization and the mechanical stress is presented in this paper. The novelty of this method consists in a particular supplying of the circuit and in measuring the voltages on diagonals. The measured quantities depends on these values. The resistor bridge does not require an additional temperature sensor.

The maximum nonlinearity error with respect to mechanical stress is 1.8% FSR and for the measurement of temperature changes is a little bigger - 2.5% FSR. It is acceptable for many industrial applications but the additional experimental tests and some upgrading is still needed.

The repeatability of the measurements (0.2%) is very good. One reason has a big influence on it - the current J is measured continually (by additional ADC) and its value is updated and dynamically corrected in microprocessor.

Furthermore the method of 2-parameter measurement with the two current supply sources can be applied for semiconductor strain gauges. They have not only higher sensitivity than the metallic ones, but at the same time, are also more dependent on temperature. This kind of compensation could be replaced by 2-parameter measurements by the **2J**-supply method with digital processing of their output signals. In such a way the proper temperature compensation could be obtained much easier.

It is also possible to combine the measurement and conditioning method of Pallas-Areny and collaborators [12, 13] with the concept of **2J** bridges for multivariable measurements.

The 2J supplied bridge circuits could be implemented to design different types of MEMS sensors which can be applied in biomechanics technique. The one example may be the human posture control system. It is a biomedical device which registers the small movements made by a patient in a standing posture. Another application may be performed in investigations of artificial limbs. These appliances work in rather large range of temperatures (-40 ÷+50 ^{O}C) and this combined nanosensor can be very useful to ensure their continuous surveillance. It will be the aim of further work by the author of this paper.

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